THE PROBLEM OF SODIUM DISTRIBUTION

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The quantity of free sodium atoms in the upper atmosphere can be determined from the ground by measuring the brightness of resonantly scattered solar radiation in the D lines[1,2]. This measurement can be made during the day and during twilight. The altitude distribution of the atoms can be determined from the ground in twilight and from rockets during the daytime again by observation of the D lines. Systematic studies made during the past decade have shown that the sodium abundance is larger in the day than it is in twilight[3,4]. The ratio is about five in midsummer and two in midwinter (Fig. 1). The daytime average values range from 12 x 10^9 atoms/cm^2 in April to 20 x 10^9 atoms/cm^2 in November. The twilight averages range from 2.5 x 10^9 atoms/cm^2 in June to 7.5 x 10^9 atoms/cm^2 in November. Confirmation of these large diurnal effects reported by Blamont and Donahue[3] has recently been obtained by Noxon[5] with his dayglow polarimeter, by Wallace and Hunten[5] and by Meier, Donahue and Blamont with rocket borne photometer experiments.

On the assumption that the distribution of sodium and its oxides is controlled by chemical oxidation and reduction processes and by eddy mixing in the mesosphere Blamont and Donahue[3] showed that a diurnal variation of the sort observed was possible provided a proper ratio of reaction rates and a sufficiently high eddy diffusion coefficient at 90 km were realized. Sodium oxidation was supposed to result from a reaction with ozone

$$Na + O_3 \rightarrow Na\,O + O_2 \qquad (1)$$

and reduction from a reaction of the oxide with atomic oxygen

$$Na\,O + O \rightarrow Na + O_2 \qquad (2)$$

Since atomic oxygen is transformed to ozone after sunset the basis for the diurnal variation in sodium was in the diurnal variation of O and O_3. In this model the sodium was predominantly in reduced form at all altitudes higher than a critical height where the O to O_3 ratio became large enough. Thus the build up in free sodium during the day would surely have occured below the twilight sodium peak and would have resulted in a daytime distribution broader than that in twilight with a maximum more than one scale height lower than the altitude of the twilight maximum.

Observation of the dayglow from sounding rockets in 1964 revealed that the distribution was not at all like the one expected from this model (Figs. 2 and 3). For example in September, 1964, above Wallops Island the abundance was measured to be 12×10^9 atoms/cm^2 but the sodium was found to be concentrated in a layer only 4 km wide (full width at half maximum) with a peak density of 4×10^4 atoms/cm^3 at 93.5 km. The twilight layer was slightly lower and contained only 2×10^9 atoms/cm^2. Evidence for a narrow daytime layer containing more sodium than the twilight layer has been obtained also by Hunten and Wallace in a rocket experiment at White Sands[6].

It can hardly be fortuitous that the layer of metallic ions, including 23^+, observed by Narcisi and Bailey[7], corresponds in altitude to the neutral sodium layer and is equally narrow. The fact that the neutral sodium (50 times as dense as the ion) is confined to the same thin layer as the sodium ion, and the density decreases with altitude above the peak with a scale height less than half that of the atmosphere in both cases points uniquely, it seems, to the presence of a concentrated source of atoms located at 93.5 km. The width of the source layer must be no greater than the atomic and ionic layers.

As a model, therefore, it is postulated here that a very thin layer of aerosols exists at 93.5 km. Sodium atoms (as well as other species) are liberated from the dust particles at a rate higher when the sun is on them than when it is not. As the atoms diffuse away from the source they can be oxidized by reaction (1) and photoionized. The condition for the appearance of a sodium distribution with a scale height H_1 is

$$k_1\, n(O_3) = D/H_1^2 \tag{3}$$

where D is the eddy diffusion coefficient. If D is 4×10^6 cm^{-2} sec^{-1}, H_1 will be 20 km provided the lifetime against oxidation is about 10^4 sec. If $n(O_3)$ is of the order of 5×10^7 cm^{-3} the rate coefficient required is 2×10^{-12} cm^{-3} sec^{-1}. This value is certainly reasonable even though no measurement is yet available.

Provided the lifetime of Na O against reduction in process (2) and against photodissociation is of the order of 10^5 seconds the ratio of the oxide to reduced sodium will be 50 at 93.5 km but only about 2×10^{-2} at 110 km. Hence free sodium tends to reappear at high altitude. It will not necessarily live long enough in the unionized state, however, to build up to an observable density at that altitude.

At 93 km the degree of Na ionization is only 2×10^{-2}. Since a sodium atom at that altitude has a mean life against photo-ionization of about 10^5 sec this means that sodium ions must be removed by some process at the rate of

5×10^{-4} per second. The only removal processes which present themselves as potentially rapid are

$$Na^+ + O_3 \rightarrow Na\,O^+ + O_2 \tag{4}$$

followed by

$$Na\,O^+ + e \rightarrow Na + O \tag{5}$$

and

$$Na^+ + X^- \rightarrow Na + X \quad . \tag{6}$$

A mutual recombination coefficient of 10^{-6} cm^3/sec would require a negative ion density of 5×10^2 in the daytime to qualify process (6) and this seems highly improbable. On the other hand the rate coefficient for the ion-molecule reaction (4) would only need to be 10^{-11} cm^{-3} sec^{-1} to put the ion to neutral ratio at its observed value. The fifty fold reduction in ozone density which should occur between 93 km and 110 km would reduce the Na to Na^+ ratio to less than unity. There is also to be considered in the ionic creation and removal balance, the effect of transport by wind shear electric fields which will tend to build up the ion density at the proper node in the east-west wind pattern. This node normally is found somewhere near 110 km.

In this picture then the sodium diffusing away from the aerosal layer is weakly ionized near 95 km and the ion density is tied to the neutral density. Both decrease rapidly with altitude because of the removal of the neutral sodium in the reaction between sodium and ozone. The sodium is predominantly in the form of Na O below 90 km and above 95 km all the way to 105 km where the oxide dissociates. There, however, after the sodium is ionized, its lifetime against formation of Na O^+ is of the order of 10^5 seconds and the predominant form is Na^+.

The possibility of creating a thin aerosol layer in the mesopause has been given some attention in connection with the formation of nocti-lucent coulds[8]. If the dust particles are charged there is a mechanism available which could produce an extremely narrow layer analagous to an ionic sporadic E layer; that is the wind shear. Thus if an atmospheric drag force appropriate to small spherical particles is assumed a particle of 10^{-7} cm radius carrying a charge of 1 emu would attain a vertical velocity of 10^4 cm sec^{-1} at 45° geomagnetic latitude when the horizontal wind velocity is 100 m sec^{-1}. Application of the wind shear theory shows that a layer of particles whose radius is 10^{-6} cm or less can be formed in a typical wind shear node during a time very short compared to one day and will have a half width of the order of 1 km. If it is assumed that 2% of the mass of the dust is sodium and that it is all released in about one day and it is also required that the dust charge density not exceed 10^4 electrons per cm^3 then a charged dust concentration adequate to produce the sodium layer can be built up if the average particle radius is 5×10^{-7} cm or greater. This is on the assumption of a single electronic charge per aerosol particle.

Still on the basis of a one day lifetime for the dust in the wind-shear concentration a dust influx of 10^{-15} gm/cm^2 sec is needed. This is to be compared with estimates for meteoric influx which range from 2×10^{-15} gm cm^{-2} sec^{-1} to 2×10^{-14} gm cm^{-2} sec^{-1}.

Since the wind shear node normally found near 95 is appropriate for concentrating negatively charged particles the dust particles would of course need to carry an excess of electrons.

The presence of slowly recombining metallic ions such as Ca^+, Mg^+, Na^+, Si^+ and Fe^+ in the ionosphere raises the possibility that these are the ions concentrated at wind shear nodes to produce sporadic E layers. Although they are minor constituents their long lifetime permits them to build up to densities of the order of 10^4 times their average density at the maxima. Thus there may be permanent maxima of meteoric ions at the proper nodes in the east-west wind profile. Although normally the density of these ions may be less than that of the major ions (NO^+ and O_2^+), fluctuations in the meteoric ion supply associated with fluctuations in the dust influx could on occasions push these peaks above the normal level of NO^+ and O_2^+ thereby producing the sporadic E layer.

A number of experiments can be suggested to elucidate the role of aerosols in the production of metallic atoms and ions in the E region. For example it would be worthwhile to employ sodium dayglow photometers and sporadic E sounders systematically to observe the same general region of the atmosphere. It is obviously necessary to make ion mass spectrometer observations with good spatial resolution in Sporadic E. It would be interesting to couple ion mass spectrometers and alkalai dayglow photometers in the same rocket probing the 90-100 km region. Aerosol detection at the same time with high spatial resolution would be very useful.

Acknowledgements

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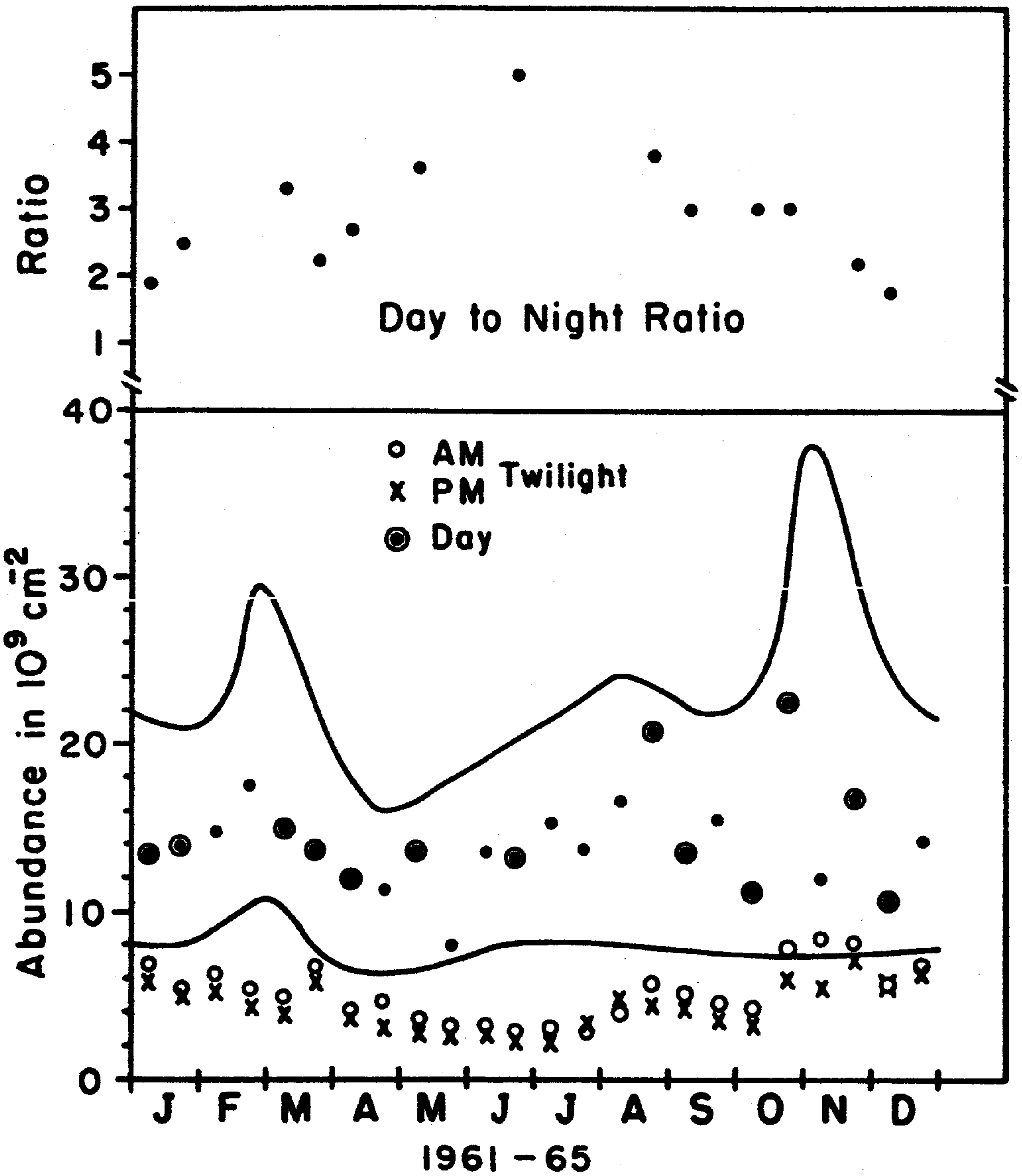
Figure Captions

Fig. 1 Semi-monthly averages of sodium abundance in daytime and twilight abundances are shown for the period August 1961-December 1965. Solid lines enclose all but at most 10% of the daytime measurements for each 15 day period. Points not encircled are for periods during which fewer than 10 samples are available. The average day to twilight abundance ratio is shown also for each semi-monthly period.

Fig. 2 Brightness of the D lines 7° above the horizon observed with a broad and narrow filter from a rocket. Solid line is theoretical brightness for a layer 4 km wide at 93.5 km.

Fig. 3 Brightness of the D lines measured from a point above the sodium layer. Solid curve is theoretical.



Ratio
5
4
3
2
1
Day to Night Ratio
40
30
20
10
0
o AM
x PM
Twilight
Day
Abundance in $10^9 cm^{-2}$
J F M A M J J A S O N D
1961 - 65

FIG. 1

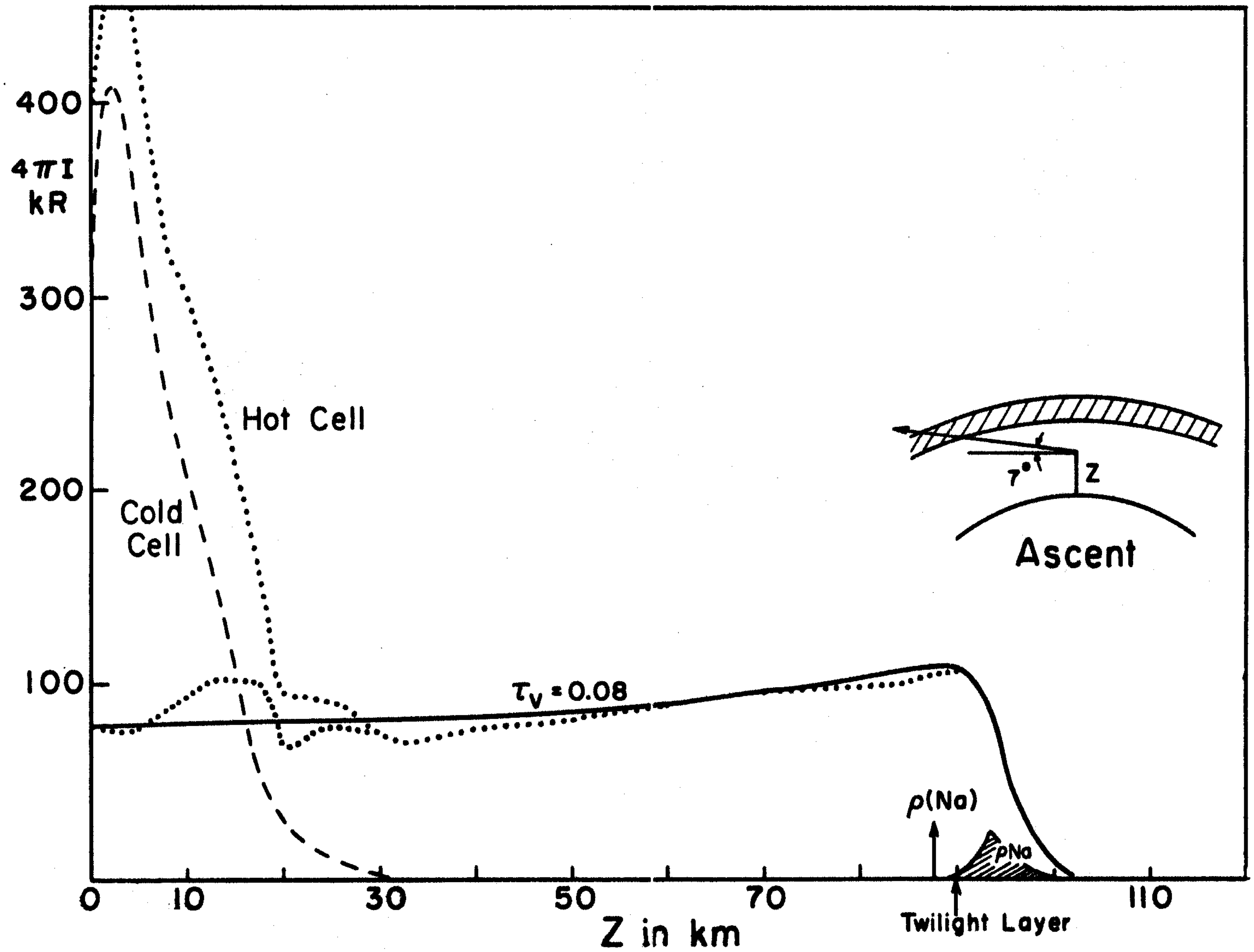
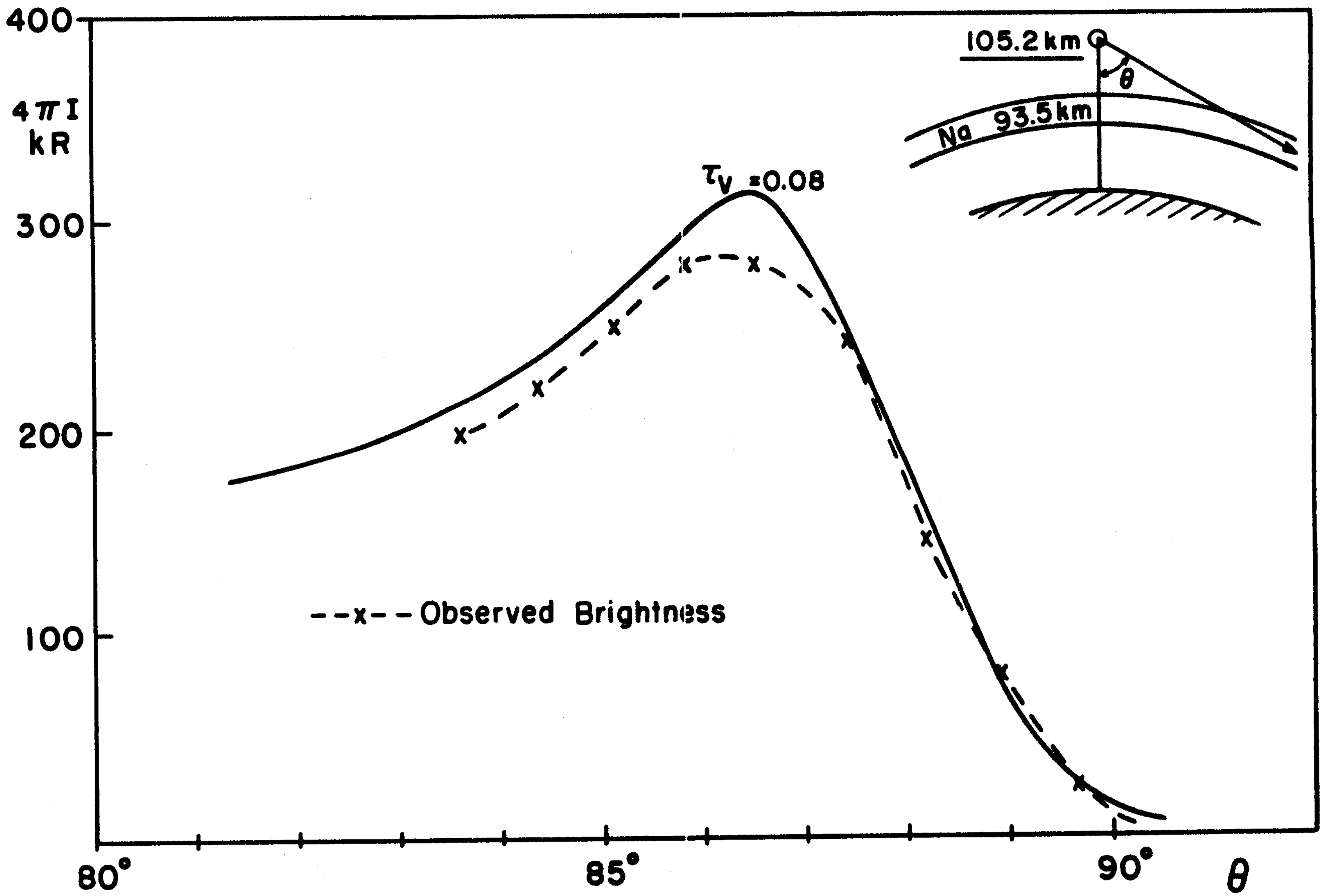

400
4πI
kR
300
200
100
Hot Cell
Cold
Cell
τV = 0.08
7°
Z
Ascent
ρ(Na)
ρNa
0
10
30
50
70
110
Z in km
Twilight Layer

FIG. 2



400
300
200
100
4πI
kR
80°
85°
90°
θ
τV =0.08
--x--Observed Brightness
105.2 km
θ
Na 93.5 km

FIG. 3